

# SUMMARY OF COMPILED PERMEABILITY WITH DEPTH MEASUREMENTS FOR BASIN FILL, IGNEOUS, CARBONATE, AND SILICICLASTIC ROCKS IN THE GREAT BASIN AND ADJOINING REGIONS

*by Stefan M. Kirby*



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## ABSTRACT

The compiled dataset presented herein includes permeability measurements from both standard groundwater aquifer tests and a variety of drill stem tests from the oil and gas industry in Utah and the Great Basin and the adjoining states of Colorado, Wyoming, and New Mexico. All measurements compiled from these sources contain basic lithology, depth, and permeability information. The dataset contains 1188 permeability measurements: 588 measurements are from siliciclastic rocks, 250 measurements are from carbonate rocks, 253 measurements are from igneous rocks, and 97 measurements are from basin fill. Based on the compiled dataset both carbonate and siliciclastic rock units may have wellbore-scale permeability greater than 10 mD at depths of more than 2000 meters. The median permeability of carbonate rock and siliciclastic rocks units at depths between 3000 and 5000 meters is 75 and 30 mD respectively. Basin fill permeability is generally greater than 1000 mD for depths less than 700 meters. Igneous rock permeability is generally greater than 1 mD for depths less than 2250 meters, and insufficient data is available at greater depth. Permeability values for given depth ranges of carbonate and siliciclastic rocks taken from global data in Ehrenberg and Nadeau (2005) are comparable to, and greater than those in the compiled dataset. Carbonate rocks generally have slightly higher permeability for a given depth than siliciclastic rocks, and would therefore be the target of choice for deep geothermal development.

## INTRODUCTION

Permeability of geologic units at depth represents a major constraint on the feasibility and development of deep seated geothermal resources. Existing data from geothermal reservoirs at depths greater than several thousand meters are generally lacking. This report combines existing permeability data from oil and gas drill stem tests and water well aquifer tests in an attempt to constrain the perme-

ability of deep geothermal reservoir targets and adjoining units in Utah and the Great Basin and the adjoining states of Colorado, New Mexico, and Wyoming.

## BACKGROUND

This summary report presents a compiled dataset of published permeability versus depth measurements for the Great Basin and several adjoining states. The dataset includes permeability measurements from both standard groundwater aquifer tests and a variety of drill stem tests from the oil and gas industry. The dataset is taken from three primary sources: the Department of Energy Gas Information System (GASIS) database (U.S. Department of Energy, 1999), a summary of aquifer test data acquired in the southern Basin and Range Province as part of the Death Valley regional aquifer study (Belcher and others, 2001), and a U.S. Geological Survey database of recent aquifer test data in Nevada (U.S. Geological Survey, 2011). All measurements compiled from these sources contain basic lithology, depth, and permeability information. Permeability measurements were converted to standard units of millidarcies (mD). In the case of aquifer test data, transmissivity measurements were converted to permeability using unit thickness data included in the original measurements. Aquifer test measurements that partially penetrate aquifers and lack constraint on unit thickness were not included in the compiled dataset. Depth values are the midpoint of the tested interval if top and bottom information was included or a simple depth if only a single depth value was given.

Permeability measurements were grouped into four units typical of the Basin and Range Province that include siliciclastic, carbonate, basin fill, and igneous rocks. These broad unit categories are meant to encompass the possible deep geothermal reservoir targets as well as adjoining units that may place important constraints on drilling and geothermal system design and operation in the Great Basin area. Unit designations from the GASIS database

were either carbonate or siliciclastic. Data presented by Belcher and others (2001) and the U.S. Geological Survey (2011) contain more detailed lithology information, and formational designations were used to group measurements based on the dominant lithology. In these cases the carbonate rock unit includes primarily Paleozoic-age limestone and/or dolomite formations. The siliciclastic rock unit includes measurements taken from quartzite, sandstone, and shale lithologies of various ages. The igneous rock unit includes all extrusive (volcanic) and intrusive (plutonic) rocks that range from tuff deposits to granites. Basin fill includes consolidated to unconsolidated sand, gravel, mud, clay, and silt deposits that fill extensional basins in the Basin and Range Province.

Measurements from the GASIS database lack complete latitude and longitude location information, but do contain oil and gas field and state location information that was used to select measurements from Utah and the adjoining states of Colorado, New Mexico, and Wyoming. The GASIS database contains no data from the Great Basin outside of Utah. Measurements from Belcher and others (2001) and the U.S. Geological Survey (2011) are located entirely within the Great Basin. Subsequent discussions subdivide the dataset based on this basic location information into measurements from Utah and the Great Basin, or all measurements that include adjoining states of Colorado, New Mexico, and Wyoming together with those from Utah and the Great Basin. Basic location information and lithologic units are combined to group and analyze the data in greater detail. The data subsets discussed in greater detail below include basin fill in the Great Basin, igneous rocks in the Great Basin, carbonate rocks in Utah and the Great Basin, siliciclastic rocks in Utah and the Great Basin, all carbonate rocks including adjoining states, and all siliclastic rocks including adjoining states.

## DATA SUMMARY

The complete dataset contains a total of 1188 compiled permeability measurements: 767 measurements of the total are from the GASIS database (U.S. Department of Energy, 1999), 378 measurements are from Belcher and others (2001), and 43 measurements are from the U.S. Geological Survey (2011) (table 1). In the dataset there are 464 measurements from Utah and the Great Basin area and an additional 724 measurements from the adjoining states of Wyoming, Colorado, and New Mexico. A total of 588 measurements are from siliciclastic rocks, 250 measurements are from carbonate rocks, 253 measurements are from igneous rocks, and 97 measurements are from basin fill.

**Table 1.** *Compiled dataset of permeability with depth measurements. ([Click to view Excel file](#)).*

Depth of measurement irrespective of lithologic unit ranges between 4.2 and 7214 meters below land surface (table 2). For the entire dataset permeability ranges across ten orders of magnitude from a minimum of 0.001 mD to a maximum value of 1,111,438 mD. Basin fill permeability measurements extend to a depth of 686 meters and measurements of permeability in igneous rocks extend to a depth of 2243 meters. Measurements for carbonate rocks in Colorado, New Mexico, and Wyoming extend to 7214 meters in depth. Within Utah and the Great Basin carbonate rock measurements extend to 3793 meters in depth. The maximum depth of measurement for all siliciclastic rocks is 5531 meters and siliciclastic rocks in Utah and the Great Basin have measurements to a depth of 4774 meters.

Figure 1 shows permeability versus depth for all 1188 measurements included in the dataset. Measurements are symbolized based on lithologic unit and general location and plotted along a logarithmic permeability scale. Permeability is highest for basin fill, carbonate rock, and igneous rock within 1000 meters of the land surface. The highest permeability values are for basin fill and carbonate rocks within the upper 500 meters. The lowest permeability values occur between 1200 and 2500 meters depth in igneous rocks and there are no measurements for igneous rocks below 2500 meters. Permeability decreases with increasing depth for all lithologic units between 0 and 2500 meters. Below this, most measurements of carbonate or siliciclastic rocks have permeability between 10 and 100 mD. Carbonate and siliciclastic rocks from Utah and the Great Basin generally have higher permeability than those for a similar depth from adjoining states (including Colorado, New Mexico, and Wyoming).

To better constrain possible permeability with depth each lithologic unit was subdivided by 500-meter depth intervals, and for all measurements in the 3000 to 5000 meter depth interval. Statistical summaries were computed using the R statistical software (R Development Core Team, 2012) and graphically represented using box and whisker plots for each depth interval (table 3, figures 2, 3, 4, and 5). Statistical values of percentile, mean, median, and geometric mean for depth intervals with fewer than five measurements have limited statistical validity and, in this case, these values are best interpreted as a general range of possible permeability at a given depth.

Median permeability values are highest for the upper 500-meter depth interval for all lithologic units except siliciclastic rocks. Data for the basin fill unit are limited to depths less than 1000 meters below land surface, and data for igneous rocks are limited to depths less than 2500 meters. Data for carbonate rocks in Utah and the Great Basin are limited to depths less than 4000 meters, and data for siliciclastic rocks in Utah and the Great Basin cover depth intervals of less than 3000 meters and between 3500 and 5000 meters.

Table 2. Summary of permeability data by lithologic unit.

Lithologic Unit	Depth (m)					Permeability (mD)			
	n <sup>1</sup>	Median	Geomean <sup>2</sup>	Minimum	Maximum	Median	Geomean	Minimum	Maximum
Great Basin basin fill	97	110	96	4.2	686	4.47E+03	2.78E+03	8.36E-02	1.77E+05
Great Basin igneous rocks	253	749	683	48.8	2243	9.96E+01	8.28E+01	1.36E-03	2.41E+05
All carbonate rocks	250	1750	1534	13.9	7214	4.10E+01	6.79E+01	1.28E-01	1.11E+06
All siliciclastic rocks	588	1999	1793	58.2	5530.9	2.50E+01	2.53E+01	2.59E-01	6.05E+03
Utah and Great Basin carbonate rocks	55	1106	686	13.9	3792.9	2.92E+02	6.10E+02	1.28E-01	1.11E+06
Utah and Great Basin siliciclastic rocks	59	1535	1283	100	4774.1	3.24E+01	1.87E+01	2.59E-01	6.05E+03

<sup>1</sup> Number of occurrences

<sup>2</sup> Geometric mean taken as the exponent of the mean of logs of either depth or permeability

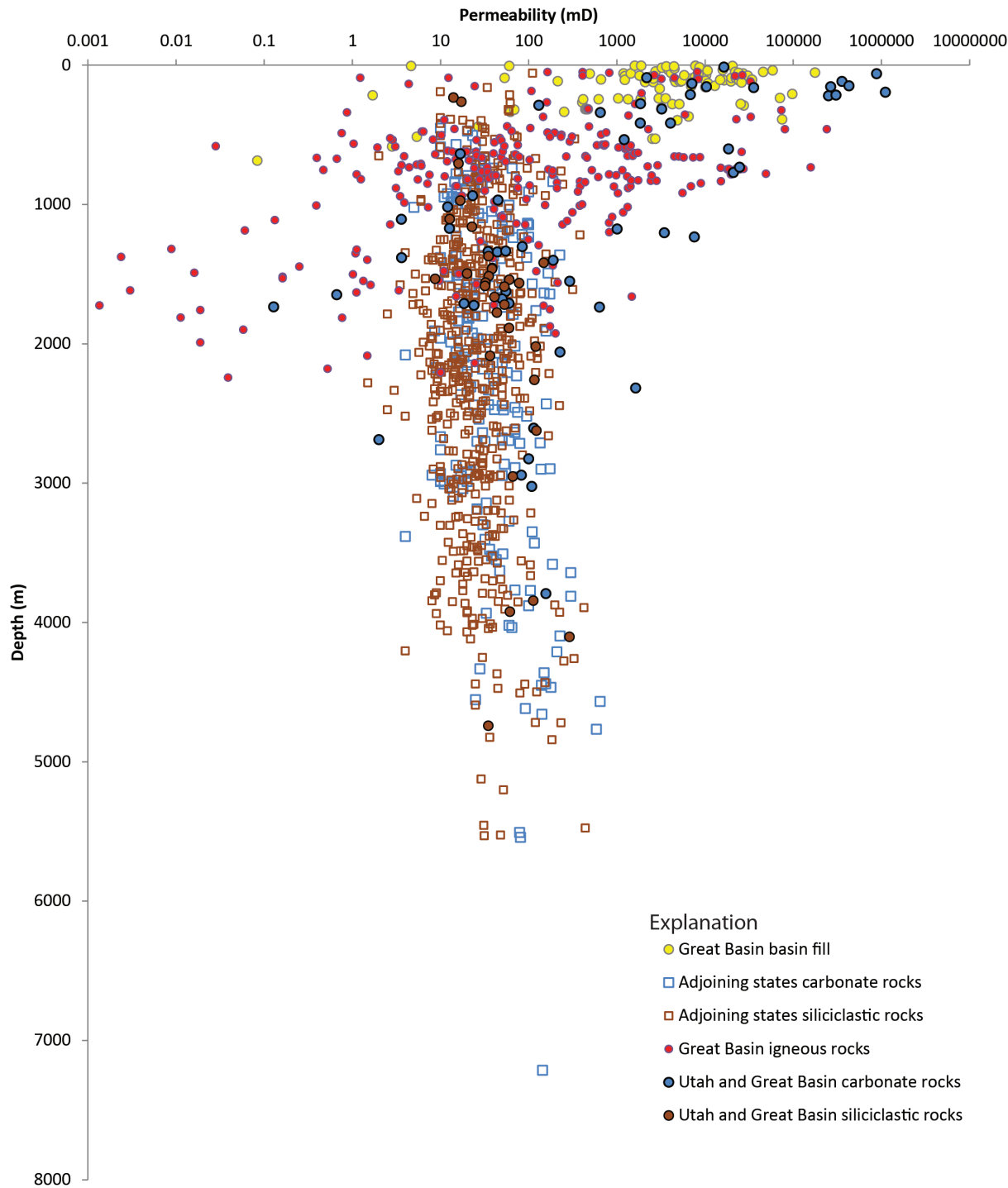


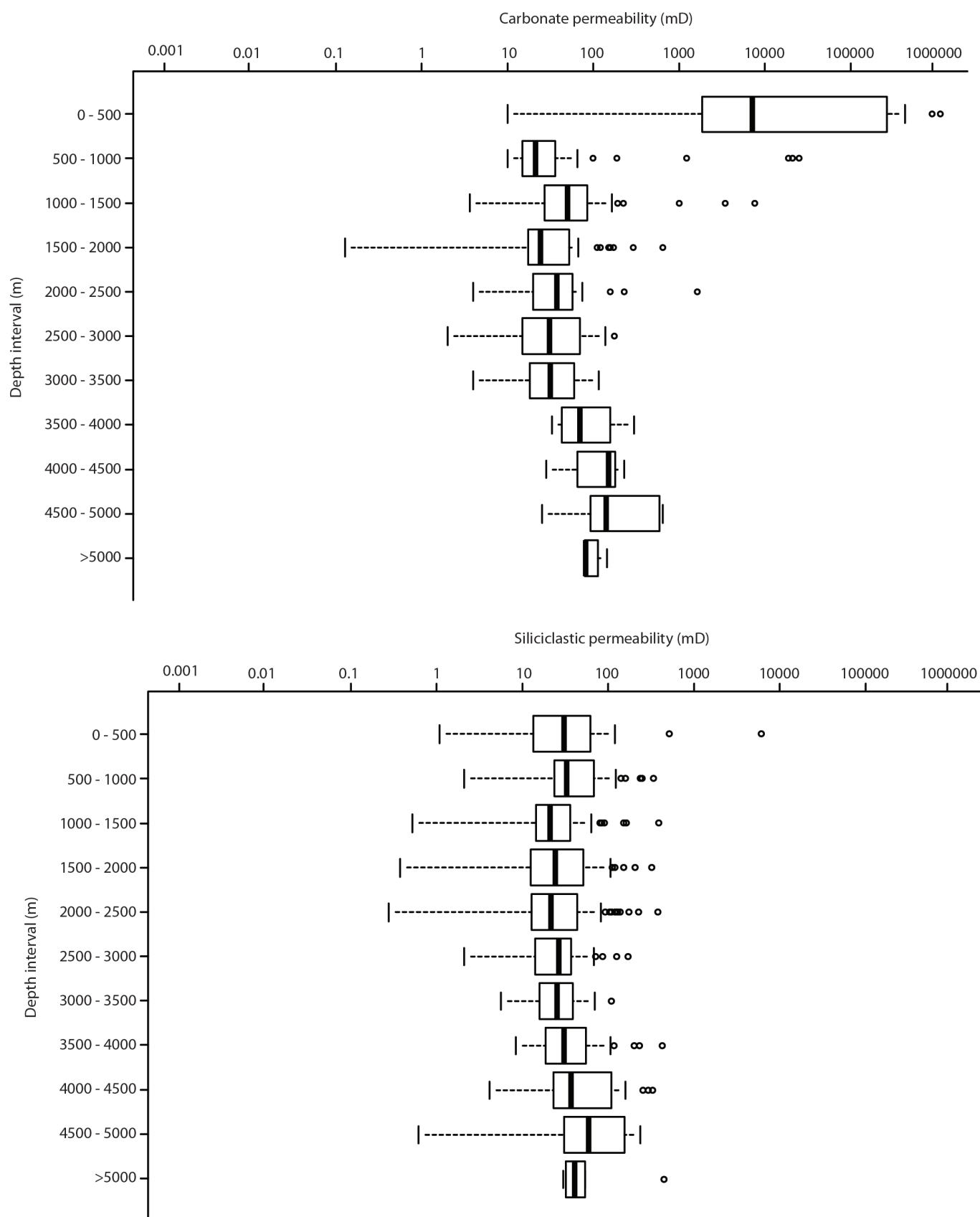
Figure 1. Permeability versus depth for basin fill, igneous, carbonate, and siliciclastic rocks.

**Table 3.** Summary of permeability data by depth intervals.

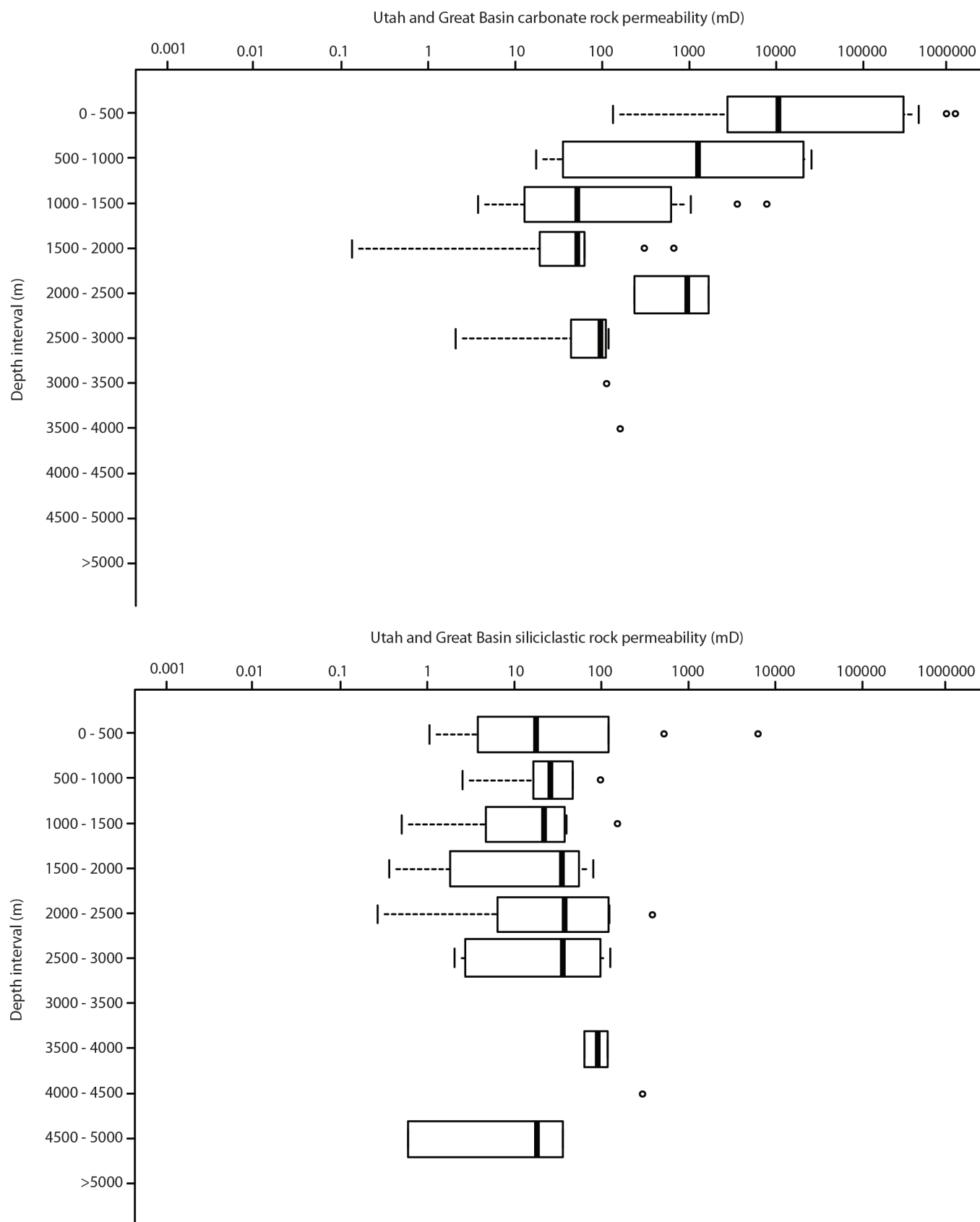
Lithologic unit	Depth <sup>1</sup>	n <sup>2</sup>	Min	10 <sup>3</sup>	25	Median <sup>4</sup>	Geomean <sup>5</sup>	75	90	Max
Great Basin basin fill	0-500	92	1.70E+00	1.70E+00	1.52E+03	4.59E+03	3.59E+03	1.54E+04	3.41E+04	1.77E+05
	500-1000	5	8.36E-02	8.36E-02	2.83E+00	5.39E+00	2.45E+01	2.53E+03	2.74E+03	2.74E+03
	1000-1500	NA	--	--	--	--	--	--	--	--
Great Basin igneous rocks	0-500	46	7.59E-01	7.59E-01	6.43E+01	5.74E+02	5.24E+02	8.11E+03	8.45E+03	2.41E+05
	500-1000	142	2.83E-02	2.83E-02	1.73E+01	1.03E+02	1.48E+02	1.35E+03	2.90E+03	1.58E+05
	1000-1500	36	2.40E-03	2.39E-03	1.30E+00	4.99E+01	1.70E+01	2.58E+02	4.06E+02	1.33E+03
	1500-2000	24	1.40E-03	1.36E-03	1.10E-01	1.48E+00	1.93E+00	9.44E+01	2.14E+02	1.48E+03
	2000-2500	5	3.91E-02	3.91E-02	5.26E-01	1.48E+00	1.50E+00	1.01E+01	1.01E+01	2.46E+01
	2500-3000	NA	--	--	--	--	--	--	--	--
All carbonate rocks	0-500	21	1.00E+01	1.00E+01	1.86E+03	7.10E+03	1.02E+04	2.66E+05	4.29E+05	1.11E+06
	500-1000	36	1.02E+01	1.00E+01	1.50E+01	2.10E+01	4.43E+01	3.56E+01	6.50E+01	2.47E+04
	1000-1500	42	3.61E+00	3.61E+00	2.70E+01	5.00E+01	5.10E+01	8.46E+01	1.66E+02	7.56E+03
	1500-2000	43	1.28E-01	1.28E-01	1.73E+01	2.40E+01	2.83E+01	5.27E+01	6.70E+01	6.37E+02
	2000-2500	30	4.00E+00	4.00E+00	2.00E+01	3.75E+01	3.90E+01	5.73E+01	7.50E+01	1.63E+03
	2500-3000	34	2.00E+00	2.00E+00	1.50E+01	3.10E+01	3.24E+01	7.00E+01	1.38E+02	1.75E+02
	3000-3500	14	4.00E+00	4.00E+00	1.80E+01	3.12E+01	3.09E+01	6.00E+01	1.16E+02	1.16E+02
	3500-4000	13	3.30E+01	3.30E+01	4.30E+01	7.00E+01	8.35E+01	1.57E+02	3.00E+02	3.00E+02
	4000-4500	9	2.80E+01	2.80E+01	6.47E+01	4.42E+01	1.13E+02	1.79E+02	2.27E+02	2.27E+02
	4500-5000	5	2.50E+01	2.50E+01	9.20E+01	1.41E+02	1.65E+02	5.85E+02	6.46E+02	6.46E+02
	>5000	3	7.90E+01	7.90E+01	8.00E+01	8.10E+01	9.72E+01	1.12E+02	1.44E+02	1.44E+02
All siliciclastic rocks	0-500	26	1.04E+00	1.04E+00	1.30E+01	2.95E+01	3.01E+01	6.10E+01	1.18E+02	6.05E+03
	500-1000	69	2.00E+00	2.00E+00	2.30E+01	3.20E+01	3.48E+01	6.70E+01	1.20E+02	3.33E+02
	1000-1500	94	4.93E-01	4.93E-01	1.40E+01	2.05E+01	2.10E+01	3.52E+01	6.20E+01	3.83E+02
	1500-2000	105	3.51E-01	3.51E-01	1.20E+01	2.34E+01	2.20E+01	5.00E+01	1.05E+02	3.17E+02
	2000-2500	111	2.59E-01	2.59E-01	1.23E+01	2.10E+01	2.27E+01	4.25E+01	8.05E+01	3.78E+02
	2500-3000	60	2.01E+00	2.01E+00	1.36E+01	2.55E+01	2.23E+01	3.61E+01	6.61E+01	1.68E+02
	3000-3500	47	5.40E+00	5.40E+00	1.55E+01	2.48E+01	2.37E+01	3.74E+01	6.80E+01	1.06E+02
	3500-4000	42	8.00E+00	8.00E+00	1.80E+01	3.00E+01	3.27E+01	5.40E+01	1.05E+02	4.24E+02
	4000-4500	20	4.00E+00	4.00E+00	2.25E+01	3.60E+01	4.24E+01	1.07E+02	1.54E+02	3.27E+02
	4500-5000	8	5.77E-01	5.77E-01	2.99E+01	5.82E+01	4.07E+01	1.52E+02	2.34E+02	2.34E+02
	>5000	6	2.90E+01	2.90E+01	3.10E+01	3.98E+01	5.61E+01	5.20E+01	5.20E+01	4.40E+02
Utah and the Great Basin carbonate rocks	0-500	19	1.30E+02	1.30E+02	2.70E+03	1.04E+04	2.04E+04	2.85E+05	4.29E+05	1.11E+06
	500-1000	7	3.40E+01	1.68E+01	3.40E+01	1.21E+03	7.97E+02	1.98E+04	2.47E+04	2.47E+04
	1000-1500	12	3.61E+00	3.61E+00	1.24E+01	4.96E+01	8.02E+01	5.98E+02	1.01E+03	7.56E+03
	1500-2000	9	1.28E-01	1.28E-01	1.85E+01	5.00E+01	2.19E+01	6.00E+01	6.00E+01	6.37E+02
	2000-2500	2	2.27E+02	2.27E+02	2.27E+02	9.29E+02	6.09E+02	1.63E+03	1.63E+03	1.63E+03
	2500-3000	4	2.00E+00	2.00E+00	4.24E+01	9.14E+01	3.71E+01	1.07E+02	1.14E+02	1.14E+02
	3000-3500	1	--	--	--	1.09E+02	--	--	--	--
	3500-4000	1	--	--	--	1.57E+02	--	--	--	--
	4000-4500	NA	--	--	--	--	--	--	--	--
	4500-5000	NA	--	--	--	--	--	--	--	--
	>5000	NA	--	--	--	--	--	--	--	--
Utah and the Great Basin siliciclastic rocks	0-500	9	1.04E+00	1.04E+00	3.65E+00	1.73E+01	3.42E+01	1.18E+02	1.18E+02	6.05E+03
	500-1000	6	2.47E+00	2.47E+00	1.60E+01	2.53E+01	2.14E+01	4.52E+01	4.52E+01	9.43E+01
	1000-1500	12	4.93E-01	4.93E-01	4.53E+00	2.14E+01	1.07E+01	3.68E+01	3.87E+01	1.48E+02
	1500-2000	16	3.51E-01	3.51E-01	1.79E+00	3.39E+01	1.25E+01	5.30E+01	7.83E+01	7.83E+01
	2000-2500	7	2.59E-01	2.59E-01	6.26E+00	3.64E+01	2.03E+01	1.18E+02	1.20E+02	3.78E+02
	2500-3000	4	2.01E+00	2.01E+00	2.65E+00	3.47E+01	1.52E+01	9.41E+01	1.22E+02	1.22E+02
	3000-3500	NA	--	--	--	--	--	--	--	--
	3500-4000	2	6.13E+01	6.13E+01	6.13E+01	8.73E+01	8.33E+01	1.13E+02	1.13E+02	1.13E+02
	4000-4500	1	--	--	--	2.90E+02	--	--	--	--
	4500-5000	2	5.77E-01	5.77E-01	5.77E-01	1.77E+01	4.48E+00	3.48E+01	3.48E+01	3.48E+01
	>5000	NA	--	--	--	--	--	--	--	--
All siliciclastic rocks	3000-5000	123	5.77E-01	1.08E+01	1.80E+01	2.99E+01	3.15E+01	4.87E+01	1.12E+02	4.40E+02
All carbonate rocks	3000-5000	44	4.00E+00	2.53E+01	3.30E+01	7.45E+01	7.07E+01	1.45E+02	2.22E+02	6.46E+02

<sup>1</sup> Depth interval in meters<sup>2</sup> Number of occurrences; NA indicates no measurements in a given depth range<sup>3</sup> Percentiles calculated using the R statistical software<sup>4</sup> Median values for depth intervals with 1 measurement are the actual measurement<sup>5</sup> Geometric mean

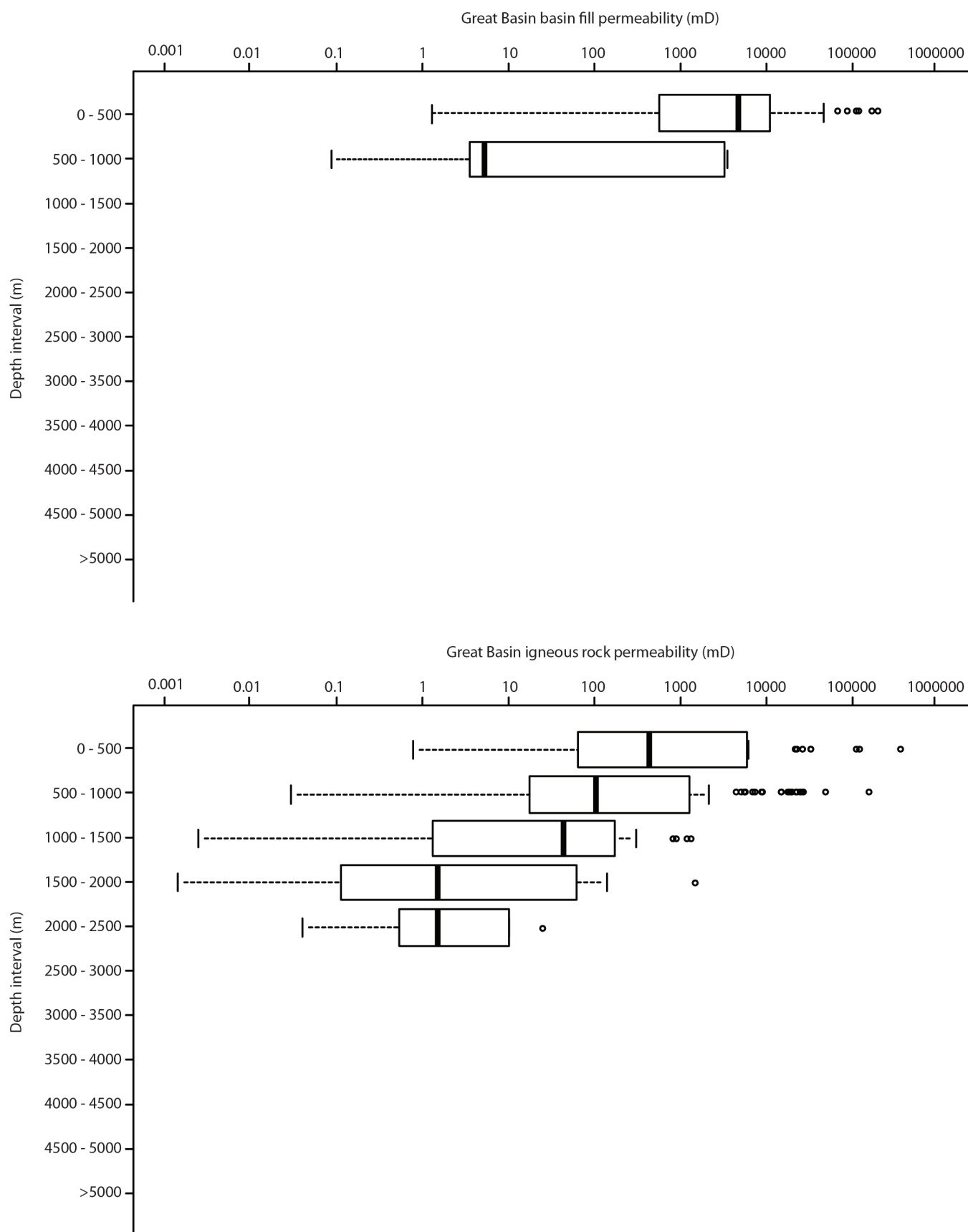




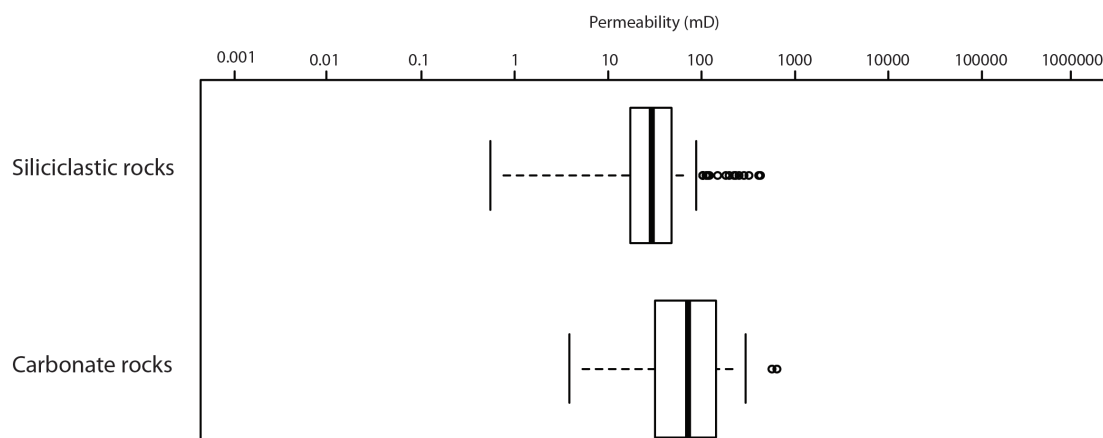
**Figure 2.** Box and whisker plots of permeability for 500-meter depth intervals for all measurements of carbonate and siliciclastic rocks. The thick vertical lines are the medians and the left and right edges of the boxes represent the 25th and 75th percentiles, respectively. The dashed lines extend to the 10th and 90th percentiles; circles indicate outliers.



**Figure 3.** Box and whisker plots of permeability for 500-meter depth intervals for carbonate and siliciclastic rocks in Utah and the Great Basin. The thick vertical lines are the medians and the left and right edges of the boxes represent the 25th and 75th percentiles, respectively. The dashed lines extend to the 10th and 90th percentiles; circles indicate outliers or single data points for a given interval.



**Figure 4.** Box and whisker plots of permeability for 500-meter depth intervals for basin fill and igneous rocks in the Great Basin. The thick vertical lines are the medians and the left and right edges of the boxes represent the 25th and 75th percentiles, respectively. The dashed lines extend to the 10th and 90th percentiles; circles indicate outliers.



**Figure 5.** Box and whisker plots of permeability for 3000 - 5000 meter depth interval for all carbonate and siliciclastic rocks. The thick vertical lines are the medians and the left and right edges of the boxes represent the 25th and 75th percentiles, respectively. The dashed lines extend to the 10th and 90th percentiles; circles indicate outliers or single data points for a given interval.

Median permeability for all carbonate rocks is 7100 mD in the upper 500-meter depth interval (figure 2, table 3). Below this depth, median permeability ranges between 21 mD for the 500 to 1000 meter depth interval to 140 mD for the 4500 to 5000 meter depth interval. Minimum permeability for all carbonate rocks ranges from 0.13 mD for the 1500 to 2000 meter depth interval to 79 mD for the greater than 5000 meter depth interval. Median permeability for all carbonate rocks in the 3000 to 5000 meter depth interval is 75 mD (table 3, figure 5). Median permeability for all siliciclastic rocks ranges between 20 mD for the 1000 to 1500 meter depth interval to 58 mD for the 4500 to 5000 meter depth interval. Minimum permeability for all siliciclastic rocks ranges from 0.26 mD for the 2000 to 2500 meter depth interval to 29 mD for the greater than 5000 meter depth interval. Median permeability for all siliciclastic rocks in the 3000 to 5000 meter depth interval is 30 mD (table 3, figure 5).

Carbonate rocks from Utah and the Great Basin have median permeability that ranges between 10,000 mD for the 0 to 500 meter depth interval to 50 mD for the 1500 to 2000 meter depth range (figure 3, table 3). Minimum permeability for carbonate rocks in Utah and the Great Basin ranges between 0.13 mD for the 1500 to 2000 meter depth interval to 230 mD for the 2000 to 2500 meter depth interval. Most permeability measurements for carbonate rocks in Utah and the Great Basin are greater than 10 mD for depths greater than 2000 meters. Median permeability for siliciclastic rocks in Utah and the Great Basin ranges from 17 mD for the 0 to 500 meter depth interval to 87 mD for the 3500 to 4000 meter depth interval; the single measurement of 290 mD for the 4000 to 4500 meter interval is significantly higher than the other median values. Minimum permeability for siliciclastic rocks in Utah and the Great Basin ranges between 0.26 mD for the 2000 to 2500 meter depth interval to 61 mD for the 3500 to 4000 meter depth interval. Minimum permeability for all depth intervals of siliciclastic rocks in Utah and the Great Basin

is generally lower than those for carbonate rocks in Utah and the Great Basin.

Median permeability for basin fill is 4590 mD for measurements less than 500 meters deep and 5 mD for the 500 to 1000 meter depth interval (figure 4, table 3). Minimum permeability for basin fill is between 0.08 mD for measurements greater than 500 meters and 1.7 mD for measurements less than 500 meters. Median permeability for igneous rocks ranges from 574 mD for the 0 to 500 meter depth interval to 1.5 mD for the 1500 to 2500 meter depth interval. Minimum permeability for igneous rocks ranges from 0.76 mD for measurements less than 500 meters to 0.001 mD for the 1500 to 2000 meter depth interval. Both igneous rocks and basin fill show a quick decline in permeability with increasing depth relative to carbonate and siliciclastic rocks.

## DISCUSSION

The compiled dataset is based on published permeability data and is therefore limited in its breadth and completeness. Much of the data presented herein, and all of the 767 measurements from the GASIS database (U.S. Department of Energy, 1999) and the 43 aquifer test results presented by the U.S. Geological Survey (2011), represent measurements of reservoir/aquifer-quality rocks. These measurements were from completed or tested intervals in lithologic units with permeability high enough to produce oil or gas or water in economic quantities. Because of this, these measured permeabilities are likely larger than actual permeability of all rocks at a given depth. Consequently, the median permeability values presented here likely represent maximum values relative to a more random sampling of permeability of various lithologies at depth. The measurements in the compiled dataset are all taken from well-bore-scale tests and permeability measured at this scale may be different than permeability measured from core or

outcrop or estimates of more regional-scale permeability based on numeric groundwater modeling or environmental tracers in groundwater. The compiled dataset includes permeability measurements from both groundwater aquifer tests and drill stem tests. Results obtained by the two methods for a given depth range and lithology generally overlap within an order of magnitude and may therefore be broadly comparable. Despite these caveats the measurements in the compiled dataset provide reasonable estimates of permeability likely to be encountered in the various rock types at depth based on the available data.

Permeability for at least several kilometers in depth has been examined by several recent studies that base their estimates either on direct measurements similar to those in the compiled dataset (Huenges and others, 1997; Ehrenberg and Nadeau, 2005; Grasle and other, 2006; Ehrenberg and others, 2009), or via various modeling exercises and/or inferences based on geochemical, geothermal, or seismic data (Ingebritsen and Manning, 1999; Saar and Manga, 2004; Rojstaczer and others, 2008; Ingebritsen and Manning, 2010). Results from direct measurements, particularly those from the datasets of Ehrenberg and Nadeau (2005) and Ehrenberg and others (2009), are broadly comparable with those in this study. Permeability values for given depth ranges of carbonate and siliciclastic rocks taken from worldwide data in Ehrenberg and Nadeau (2005) are equal to or slightly greater than those in the compiled dataset. This overlap among permeability estimates based on very different data and methodologies lends validity to the results presented in this study and potentially expands the geographic area over which they may apply.

Based on the compiled dataset both carbonate and siliciclastic rock units may have wellbore-scale permeability greater than 10 mD at depths of more than 2000 meters. The median permeability of carbonate rock and siliciclastic rocks units at depths between 3000 and 5000 meters is 75 and 30 mD respectively. Carbonate rocks generally have slightly higher permeability for a given depth than siliciclastic rocks and would therefore be the target of choice for deep geothermal development. However, deep siliciclastic rocks, possibly including fractured quartzite typical of this depth range in the Great Basin, may also be viable geothermal reservoir targets, at least locally. Igneous and basin-fill units lack measurements at depths greater than 2500 and 1000 meters, respectively, and would necessarily have higher risk with respect to permeability at depths beyond those included in the compiled dataset.

## ACKNOWLEDGMENTS

Partial funding for this project was provided by DOE grant award DE-EE0005128/000. This report benefitted from discussions with Rick Allis, Paul Inkenbrandt, and Christian Hardwick. Prompt and thorough reviews from Mike Lowe, Michael Hylland, Kimm Harty, and Rick Allis im-

proved the content of the report.

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